# MIGRATION OF JUPITER-FAMILY COMETS AND RESONANT ASTEROIDS TO NEAR-EARTH SPACE

S. I. Ipatov[1] and J. C. Mather[2]

[1](1) *George Mason University, USA; (2) NASA/GSFC, Mail Code 685, Greenbelt, MD 20771, USA; e-mail: siipatov@hotmail.com (for correspondence); (3) Institute of Applied Mathematics, Moscow, Russia*

[2]*NASA/GSFC, Mail Code 685, Greenbelt, MD 20771, USA*

## ABSTRACT

The orbital evolution of about 20000 Jupiter-crossing objects and 1500 resonant asteroids under the gravitational influence of planets was investigated. The rate of their collisions with the terrestrial planets was estimated by computing the probabilities of collisions based on random-phase approximations and the orbital elements sampled with a 500 yr step. The Bulirsh-Stoer and a symplectic orbit integrators gave similar results for orbital evolution, but sometimes gave different collision probabilities with the Sun. For orbits close to that of Comet 2P, the mean collision probabilities of Jupiter-crossing objects with the terrestrial planets were greater by two orders of magnitude than for some other comets. For initial orbital elements close to those of Comets 2P, 10P, 44P and 113P, a few objects ($\sim$0.1%) got Earth-crossing orbits with semi-major axes $a$<2 AU and moved in such orbits for more than 1 Myr (up to tens or even hundreds of Myrs). Some of them even got inner-Earth orbits (i.e., with aphelion distance $Q$<0.983 AU) and Aten orbits. Most former trans-Neptunian objects that have typical near-Earth object orbits moved in such orbits for millions of years (if they did not disintegrate into mini-comets), so during most of this time they were extinct comets.

## INTRODUCTION

The orbits of more than 70,000 main-belt asteroids, 1000 near-Earth objects (NEOs), 670 trans-Neptunian objects (TNOs), and 1000 comets are known. Most of the small bodies are located in the main asteroid and trans-Neptunian (Edgeworth-Kuiper) belts and in the Oort cloud. These belts and the cloud are considered to be the main sources of the objects that could collide with the Earth. About 0.4% of the encounters within 0.2 AU of the Earth are from periodic comets (http://cfa-www.harvard.edu/iau/lists/CloseApp.html), and 6 out of 20 recent approaches of comets with the Earth within 0.102 AU were due to periodic comets (http://cfa-www.harvard.edu/iau/lists/ClosestComets.html). So the fraction of close encounters with the Earth due to active comets is $\sim$1%. Reviews of the asteroid and comet hazard were given in [1]-[3]. Many scientists [3]-[5] believe that asteroids are the main source of NEOs (i.e.

objects with perihelion distance $q$<1.3 AU). Bottke et al. [3] considered that there are 200±140 km-sized Jupiter-family comets at $q$<1.3 AU, with ∼80% of them being extinct comets.

Duncan et al. [6] and Kuchner [7] investigated the migration of TNOs to Neptune's orbit, and Levison and Duncan [8] studied the migration from Neptune's orbit to Jupiter's orbit. Ipatov and Hahn [9] considered the migration of 48 Jupiter-crossing objects (JCOs) with initial orbits close to the orbit of Comet P/1996 R2 and found that on average such objects spend ∼ 5000 yr in orbits which cross both the orbits of Jupiter and Earth. Using these results and additional orbit integrations, and assuming that there are $5 \times 10^9$ 1-km TNOs with $30<a<50$ AU [10], Ipatov [1],[2],[11] found that about $10^4$ 1-km former TNOs are Jupiter-crossers now and 10-20% or more 1-km Earth-crossers could have come from the Edgeworth-Kuiper belt into Jupiter-crossing orbits. Note that previous estimates of the number of bodies with diameter $d\geq1$ km and $30\leq a\leq50$ AU were larger: $10^{10}$ [12] and $10^{11}$ [13] In the present paper we use the estimates from [2], but now include a much larger number of JCOs. Preliminary results were presented by Ipatov [14]-[16], who also discussed the formation of TNOs and asteroids, and in [17].

## COLLISION PROBABILITIES IN THE MODEL OF FIXED ORBITAL ELEMENTS

Table 1. Characteristic collision times $T_f$ (in Myr) of minor bodies with planets, coefficient $k$, and number $N_f$ of simulated objects for the set of NEOs known in 2001.

| | Atens | | | Apollos | | | Amors | | | NEOs | | | JFCs | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Planet | $T_f$ | $k$ | $N_f$ | $T_f$ | $k$ | $N_f$ | $T_f$ | $k$ | $N_f$ | $T_f$ | $k$ | $N_f$ | $T_f$ | $k$ |
| Venus | 106 | 1.2 | 94 | 186 | 1.7 | 248 | | – | | 154 | 1.5 | 343 | 2900 | 2.5 |
| Earth | 15 | 0.9 | 110 | 164 | 1.4 | 643 | 211 | 2.0 | 1 | 67 | 1.1 | 756 | 2200 | 2.3 |
| Mars | 475 | 0.4 | 6 | 4250 | 0.9 | 574 | 5810 | 1.1 | 616 | 4710 | 1.0 | 1197 | 17000 | 1.8 |

In this section we estimate the probabilities of collisions of near-Earth objects with planets in the model of fixed orbital elements. As the actual collisions of migrating objects with terrestrial planets are rare, we use an approximation of random phases and orientations to estimate probabilities of collision for families of objects with similar orbital elements. We suppose that their semi-major axes $a$, eccentricities $e$ and inclinations $i$ are fixed, but the orientations of the orbits can vary. When a minor body collides with a planet at a distance $R$ from the Sun, the characteristic time to collide, $T_f$, is a factor of $k = v/v_c = \sqrt{2a/R - 1}$ times that computed with an approximation of constant velocity, where $v$ is the velocity at the point where the orbit of the body crosses the orbit of the planet, and $v_c$ is the velocity for the same semi-major axis and a circular orbit. This coefficient $k$ modifies the formulas obtained by Ipatov [1],[18] for characteristic collision and close encounter times of two objects moving around the Sun in crossing orbits. These formulas also depend on the synodic period and improve on Öpik's formulas when the semi-major axes of the objects are close to each other. As an example, at $e$=0.7 and $a$=3.06 AU, we have $k$=2.26.

Based on these formulas, we calculated probabilities ($1/T_f$) for ∼ 1300 NEOs, including 343 Venus-crossers, 756 Earth-crossers and 1197 Mars-crossers. The values of $T_f$ (in Myr), $k$, and the number $N_f$ of objects considered are presented in Table 1. We considered separately the Atens, Apollos, Amors, and several Jupiter-family comets (JFCs). The relatively small values

Table 2. Semi-major axes (in AU), eccentricities and inclinations of considered comets

| | $a_\circ$ | $e_\circ$ | $i_\circ$ | | $a_\circ$ | $e_\circ$ | $i_\circ$ | | $a_\circ$ | $e_\circ$ | $i_\circ$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2P | 2.22 | 0.85 | 12° | 9P | 3.12 | 0.52 | 10° | 10P | 3.10 | 0.53 | 12° |
| 22P | 3.47 | 0.54 | 4.7° | 28P | 6.91 | 0.78 | 14° | 39P | 7.25 | 0.25 | 1.9° |
| 44 P | 3.53 | 0.46 | 7.0 | | | | | | | | |

of $T_f$ for Atens and for all NEOs colliding with the Earth are due to several Atens with small inclinations discovered during the last three years. If we increase the inclination of the Aten object 2000 SG344 from $i$=0.1° to $i$=1°, then for collisions with the Earth we find $T$=28 Myr and $k$=0.84 for Atens and $T$=97 Myr and $k$=1.09 for NEOs. These times are much longer, and illustrate the importance of rare objects.

**INITIAL DATA**

As the migration of TNOs to Jupiter's orbit was investigated by several authors, we have made a series of simulations of the orbital evolution of JCOs under the gravitational influence of planets. We omitted the influence of Mercury (except for Comet 2P) and Pluto. The orbital evolution of about 9352 and 10301 JCOs with initial periods $P_a$<20 yr was integrated with the use of the Bulirsh-Stoer (BULSTO code [19]) and symplectic (RMVS3 code) methods, respectively. We used the integration package of Levison and Duncan [20].

In the first series of runs (denoted as $n1$) we calculated the evolution of 3100 JCOs moving in initial orbits close to those of 20 real comets with period 5<$P_a$<9 yr, and in the second series of runs (denoted as $n2$) we considered 7250 JCOs moving in initial orbits close to those of 10 real comets (with numbers 77, 81, 82, 88, 90, 94, 96, 97, 110, 113) with period 5<$P_a$<15 yr. In other series of runs, initial orbits were close to those of a single comet (2P, 9P, 10P, 22P, 28P, 39P, and 44P). In order to compare the orbital evolution of comets and asteroids, we also investigated the orbital evolution of asteroids initially moving in the 3:1 and 5:2 resonances with Jupiter. The number of objects in one run usually was ≤250.

In most JCO cases the time $\tau$ when perihelion was passed was varied with a step $d\tau$≤1 day (i.e., $\nu$ was varied with a step <0.2°). Near the $\tau$ estimated from observations, we used smaller steps. In most JCO cases the range of initial values of $\tau$ was less than several tens of days. For asteroids, we varied initial values of $\nu$ and the longitude of the ascending node from 0 to 360°. The approximate values of initial orbital elements ($a$ in AU, $i$ in deg) are presented in Table 2. We initially integrated the orbits for $T_S$≥10 Myr. After 10 Myr we tested whether some of remaining objects could reach inside Jupiter's orbit; if so, the calculations were usually continued. Therefore the results for orbits crossing or inside Jupiter's orbit were the same as if the integrations had been carried to the entire lifetimes of the objects. For Comet 2P and resonant asteroids, we integrated until all objects were ejected into hyperbolic orbits or collided with the Sun. In some previous publications we have used smaller $T_S$, so these new data are more accurate.

In our runs, planets were considered as material points so literal collisions did not occur. However, using the formulas of the previous section, and the orbital elements sampled with a 500 yr step, we calculated the mean probability $P$ of collisions. We define $P$ as $P_\Sigma/N$, where $P_\Sigma$ is the probability for all $N$ objects of a collision of an object with a planet during its lifetime, the mean time $T$=$T_\Sigma/N$ during which perihelion distance $q$ of an object was less than the semi-major axis $a_{pl}$ of the planet, the mean time $T_d$ (in Kyr) spent in orbits with $Q$<4.2 AU, and the

Table 3. Mean probability $P$=$10^{-6}P_r$ of a collision of an object with a planet (Venus=V, Earth=E, Mars=M) during its lifetime, mean time $T$ (in Kyr) during which $q$<$a_{pl}$, $T_c$=$T/P$ (in Gyr), mean time $T_J$ (in Kyr) spent in Jupiter-crossing orbits, mean time $T_d$ (in Kyr) spent in orbits with $Q$<4.2 AU, and ratio $r$ of times spent in Apollo and Amor orbits. Results from BULSTO code at $10^{-9}$≤$\varepsilon$≤$10^{-8}$ (marked as $10^{-9}$) and at $\varepsilon$≤$10^{-12}$ (marked as $10^{-12}$) and with RMVS3 code at integration step $d_s$. The series of runs with a few excluded objects that had the largest probabilities of collision with the Earth are marked by *.

| | | | V | V | E | E | E | M | M | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\varepsilon$ or $d_s$ | $N$ | $P_r$ | $T$ | $P_r$ | $T$ | $T_c$ | $P_r$ | $T$ | $r$ | $T_J$ | $T_d$ |
| $n1$ | $10^{-9}$ | 1900 | 2.42 | 4.23 | 4.51 | 7.94 | 1.76 | 6.15 | 30.0 | 0.7 | 119 | 20 |
| $n1$ | ≤$10^d$ | 1200 | 25.4 | 13.8 | 40.1 | 24.0 | 0.60 | 2.48 | 35.2 | 3.0 | 117 | 25.7 |
| $n1$ | ≤$10^d$ | 1199* | 7.88 | 9.70 | 4.76 | 12.6 | 2.65 | 0.76 | 16.8 | 2.8 | 117 | 10.3 |
| $n2$ | $10^{-9}$ | 1000 | 10.2 | 27.5 | 14.7 | 43.4 | 2.95 | 2.58 | 62.6 | 3.1 | 187 | 8.3 |
| $n2$ | ≤$10^d$ | 6250 | 17.9 | 28.2 | 17.3 | 40.8 | 2.36 | 3.17 | 63.1 | 3.2 | 147 | 26.5 |
| 2P | $10^{-9}$ | 501* | 141 | 345 | 110 | 397 | 3.61 | 10.5 | 430 | 18. | 173 | 249 |
| 2P | $10^{-12}$ | 100 | 321 | 541 | 146 | 609 | 4.2 | 14.8 | 634 | 27. | 20 | 247 |
| 2P | $10^d$ | 251 | 860 | 570 | 2800 | 788 | 0.28 | 294 | 825 | 22. | 0.29 | 614 |
| 2P | $10^d$ | 250* | 160 | 297 | 94.2 | 313 | 3.32 | 10.0 | 324 | 35. | 0.29 | 585 |
| 9P | $10^{-9}$ | 800 | 1.34 | 1.76 | 3.72 | 4.11 | 1.10 | 0.71 | 9.73 | 1.2 | 96 | 2.6 |
| 9P | $10^d$ | 400 | 1.37 | 3.46 | 3.26 | 7.84 | 2.40 | 1.62 | 23.8 | 1.1 | 128 | 8.0 |
| 10P | $10^{-9}$ | 2149* | 28.3 | 41.3 | 35.6 | 71.0 | 1.99 | 10.3 | 169. | 1.6 | 122 | 107 |
| 10P | ≤$10^d$ | 450 | 14.9 | 30.4 | 22.4 | 41.3 | 1.84 | 6.42 | 113. | 1.5 | 85 | 44. |
| 22P | $10^{-9}$ | 1000 | 1.44 | 2.98 | 1.76 | 4.87 | 2.77 | 0.74 | 11.0 | 1.6 | 116 | 1.5 |
| 22P | $10^d$ | 250 | 0.68 | 2.87 | 1.39 | 4.96 | 3.57 | 0.60 | 11.5 | 1.5 | 121 | 0.6 |
| 28P | $10^{-9}$ | 750 | 1.7 | 21.8 | 1.9 | 34.7 | 18.3 | 0.44 | 68.9 | 1.9 | 443 | 0.1 |
| 28P | $10^d$ | 250 | 3.87 | 35.3 | 3.99 | 59.0 | 14.8 | 0.71 | 109. | 2.2 | 535 | 3.3 |
| 39P | $10^{-9}$ | 750 | 1.06 | 1.72 | 1.19 | 3.03 | 2.55 | 0.31 | 6.82 | 1.6 | 94 | 2.7 |
| 39P | $10^d$ | 250 | 2.30 | 2.68 | 2.50 | 4.22 | 1.69 | 0.45 | 7.34 | 2.2 | 92 | 0.5 |
| 44P | $10^{-9}$ | 500 | 2.58 | 15.8 | 4.01 | 24.9 | 6.21 | 0.75 | 46.3 | 2.0 | 149 | 8.6 |
| 44P | $10^d$ | 1000 | 3.91 | 5.88 | 5.84 | 9.69 | 1.66 | 0.77 | 16.8 | 2.3 | 121 | 2.9 |

mean time $T_J$ during which an object moved in Jupiter-crossing orbits. The values of $P_r$=$10^6P$, $T_J$, $T_d$, and $T$ are shown in Tables 3-4. Here $r$ is the ratio of the total time interval when orbits are of Apollo type ($a$>1 AU, $q$=$a(1-e)$<1.017 AU) at $e$<0.999 to that of Amor type (1.017<$q$<1.3 AU) and $T_c$=$T/P$ (in Gyr). In almost all runs $T$ was equal to the mean time in planet-crossing orbits and $1/T_c$ was a probability of a collision per year (similar to $1/T_f$).

In Table 5 for several objects that had large collision probabilities with the Earth, we present times (Myr) spent by these objects in orbits typical for inner-Earth objects (IEOs, $Q$<0.983 AU), Aten ($a$<1 AU and $Q$>0.983 AU), Al2 ($q$<1.017 AU and 1<$a$<2 AU), Apollo, and Amor objects, and also probabilities of collisions with Venus ($p_v$), Earth ($p_e$), and Mars ($p_m$) during their lifetimes $T_{lt}$ (in Myr). Objects 44P and 113P presented in Table 5 were not included in the lines $n1$ and $n2$ marked by * in Table 3, respectively, and objects 2P and 10P with BULSTO were not included in the lines for the corresponding series of runs in Table 3 with $N$=250 for 2P and $N$=2149 for 10P.

Table 4. Same as for Table 2, but for resonant asteroids. $i_o$=10$^o$ at $e_o$=0.15, and $i_o$=5$^o$ at $e_o$=0.05.

| | | | | V | V | E | E | E | M | M | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $e_o$ | $\varepsilon$ or $d_s$ | $N$ | $P_r$ | $T$ | $P_r$ | $T$ | $T_c$ | $P_r$ | $T$ | $r$ | $T_J$ | $T_d$ |
| 3 : 1 | 0.15 | $10^{-9}$ | 288 | 1286 | 1886 | 1889 | 2747 | 1.45 | 488 | 4173 | 2.7 | 229 | 5167 |
| 3 : 1 | 0.15 | $\leq 10^{-12}$ | 70 | 1162 | 1943 | 1511 | 5901 | 3.91 | 587 | 803 | 4.6 | 326 | 8400 |
| 3 : 1 | 0.15 | $10^d$ | 142* | 27700 | 8617 | 2725 | 9177 | 3.37 | 1136 | 9939 | 16. | 1244 | 5000 |
| 5 : 2 | 0.15 | $10^{-9}$ | 288 | 101 | 173 | 318 | 371 | 1.16 | 209 | 1455 | 0.5 | 233 | 1634 |
| 5 : 2 | 0.15 | $10^{-12}$ | 50 | 130 | 113 | 168 | 230 | 1.37 | 46.2 | 507 | 1.4 | 166 | 512 |
| 5 : 2 | 0.15 | $10^d$ | 144 | 58.6 | 86.8 | 86.7 | 174 | 2.01 | 17 | 355 | 1.7 | 224 | 828 |
| 3 : 1 | 0.05 | $10^{-9}$ | 144 | 200 | 420 | 417 | 759 | 1.82 | 195 | 1423 | 2.1 | 157 | 2620 |
| 3 : 1 | 0.05 | $10^d$ | 144 | 10051 | 2382 | 6164 | 4198 | 0.68 | 435 | 5954 | 2.5 | 235 | 18047 |
| 5 : 2 | 0.05 | $10^{-9}$ | 144 | 105 | 114 | 146 | 214 | 1.47 | 42 | 501 | 1.5 | 193 | 996 |
| 5 : 2 | 0.05 | $10^d$ | 144 | 148 | 494 | 173 | 712 | 4.12 | 51 | 1195 | 2.3 | 446 | 984 |

## ORBITAL EVOLUTION OBTAINED BY DIRECT INTEGRATIONS

Here and in Figs. 1, 2a-c, 3-5 we present the results obtained by the Bulirsh-Stoer method (BULSTO code [19]) with the integration step error less than $\varepsilon \in [10^{-9}$-$10^{-8}]$, and in the next section we compare them with those of BULSTO with $\varepsilon \leq 10^{-12}$ and a symplectic method.

Table 5. Times (Myr) spent by six objects in various orbits, and probabilities of collisions with Venus ($p_v$), Earth ($p_e$), and Mars ($p_m$) during their lifetimes $T_{lt}$ (in Myr)

| | $d_s$ or $\varepsilon$ | IEOs | Aten | Al2 | Apollo | Amor | $T_{lt}$ | $p_v$ | $p_e$ | $p_m$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 2P | $10^{-8}$ | 0.1 | 83 | 249 | 251 | 15 | 352 | 0.224 | 0.172 | 0.065 |
| 10P | $10^{-8}$ | 10 | 3.45 | 0.06 | 0.06 | 0.05 | 13.6 | 0.665 | 0.344 | 0.001 |
| 2P | $10^d$ | 12 | 33.6 | 73.4 | 75.6 | 4.7 | 126 | 0.18 | 0.68 | 0.07 |
| 44P | $10^d$ | 0 | 0 | 11.7 | 14.2 | 4.2 | 19.5 | 0.02 | 0.04 | 0.002 |
| 113P | $6^d$ | 0 | 0 | 56.8 | 59.8 | 4.8 | 67 | 0.037 | 0.016 | 0.0001 |
| resonance 3 : 1 | $10^{-12}$ | 0 | 0 | 20 | 233.5 | 10.4 | 247 | 0.008 | 0.013 | 0.0007 |

The results showed that most of the probability of collisions of former JCOs with the terrestrial planets is due to a small (∼0.1-1%) fraction that orbited for several Myr with aphelion $Q$<4.7 AU. Some had typical asteroidal and NEO orbits and reached $Q$<3 AU for several Myr. Time variations in orbital elements of JCOs obtained by the BULSTO code are presented in Figs. 1, 2a-b. Plots in Fig. 1 are more typical than those in Fig. 2a-b, which were obtained for two JCOs with the highest probabilities of collisions with the terrestrial planets. Fig. 2c shows the plots for an asteroid from the 3:1 resonance with Jupiter. The results obtained by a symplectic code for two JCOs are presented in Fig. 2d-e. Large values of $P$ for Mars in the $n1$ runs were caused by a single object with a lifetime of 26 Myr.

The total times for Earth-crossing objects were mainly due to a few tens of objects with high collision probabilities. Of the JCOs with initial orbits close to those of 10P and 2P, six and nine respectively moved into Apollo orbits with $a$<2 AU (Al2 orbits) for at least 0.5 Myr each,

and five of them remained in such orbits for more than 5 Myr each. The contribution of all the other objects to Al2 orbits was smaller. Only one and two JCOs reached IEO and Aten orbits, respectively.

Table 6. Times (in Myr) spent by $N$ JCOs and asteroids during their lifetimes, with results for first 50 Myr in [ ].

| | Method | $N$ | IEOs | Aten | Al2 | Apollo | Amor |
|---|---|---|---|---|---|---|---|
| JCOs | BULSTO | 9352 | 10 | 86 | 412 | 727 | 192 |
| JCOs without 2P | BULSTO | 8800 | 10 | 3.45 | 24 | 273 | 165 |
| $n1$ | RMVS3 | 1200 | 0 | 0 | 12 | 30 | 10 |
| $n2$ | RMVS3 | 6250 | 0 | 0 | 58 | 267 | 83 |
| $3:1$ | BULSTO | 288 | 13 | 4.5 | 433 [190] | 790 [540] | 290 [230] |
| $5:2$ | BULSTO | 288 | 0 | 0 | 17 [2] | 113 [90] | 211 [90] |

One former JCO (Fig. 2a), which had an initial orbit close to that of 10P, moved in Aten orbits for 3.45 Myr, and the probability of its collision with the Earth from such orbits was 0.344 (so $T_c$=10 Myr was even smaller than the values of $T_f$ presented in Table 1; i.e., this object had smaller $e$ and $i$ than typical observed Atens), greater than that for the 9350 other simulated former JCOs during their lifetimes (0.17). It also moved for about 10 Myr in inner-Earth orbits before its collision with Venus, and during this time the probability $P_V$=0.655 of its collision with Venus was greater ($P_V$≈3 for the time interval presented in Fig. 2a) than that for the 9350 JCOs during their lifetimes (0.15). At $t$=0.12 Myr orbital elements of this object jumped considerably and the Tisserand parameter increased from $J$<3 to $J$>6, and $J$>10 during most of its lifetime. Another object (Fig. 2b) moved in highly eccentric Aten orbits for 83 Myr, and its lifetime before collision with the Sun was 352 Myr. Its probability of collisions with Earth, Venus and Mars during its lifetime was 0.172, 0.224, and 0.065, respectively. These two objects were not included in Table 3. Ipatov [21] obtained the migration of JCOs into IEO and Aten orbits using the approximate method of spheres of action for taking into account the gravitational interactions of bodies with planets. In the present paper we consider only the integration into the future. Ipatov and Hahn [9] integrated the evolution of Comet P/1996 R2 both into the future and into the past, in this case the mean time $T_E$ during which a JCO was moving in Earth-crossing orbits is $T_E = 5 \times 10^3$ yr. The ratio $P_S$ of the number of objects colliding with the Sun to the total number of escaped (collided or ejected) objects was less than 0.015 for the considered runs (except for 2P).

Ratio $P_S$ of objects colliding with the Sun to those colliding with planets or ejected

| Series | $n1$ | $9P$ | $10P$ | $22P$ | $28P$ | $39P$ | $44P$ |
|---|---|---|---|---|---|---|---|
| $P_S$ | 0.0005 | 0 | 0.014 | 0.002 | 0.007 | 0 | 0.004 |

Some former JCOs spent a long time in the 3:1 resonance with Jupiter (Fig. 1a-b) and with 2<$a$<2.6 AU. Other objects reached Mars-crossing orbits for long times. We conclude that JCOs can supply bodies to the regions which are considered by many scientists [3] to belong to the main sources of NEOs, and that those rare objects that make transitions to typical NEO

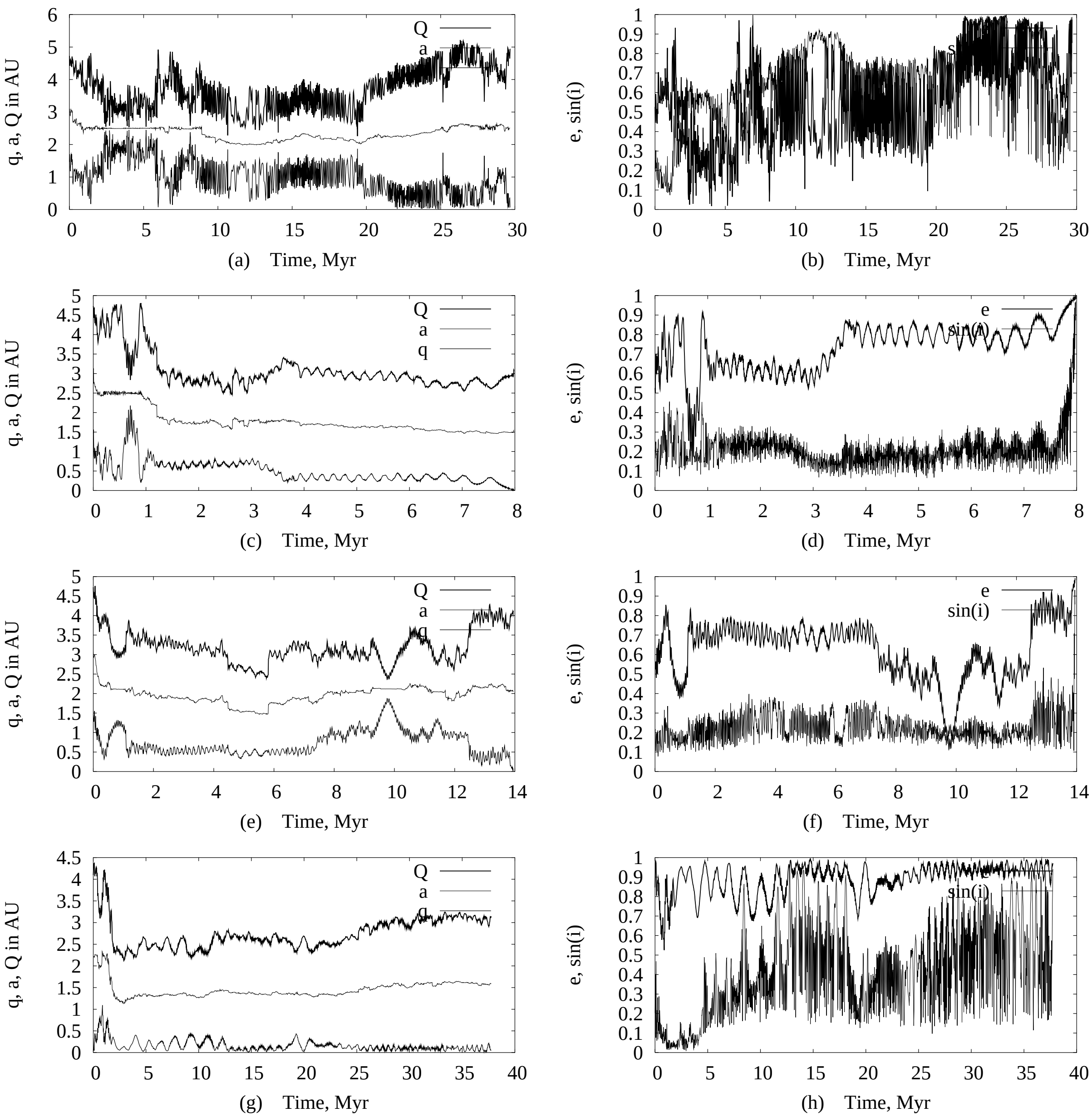


Fig. 1. Time variations in $a$, $e$, $q$, $Q$, sin$(i)$ for a former JCO in initial orbit close to that of Comet 10P (a-f), or Comet 2P (g-h). Results from BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$.

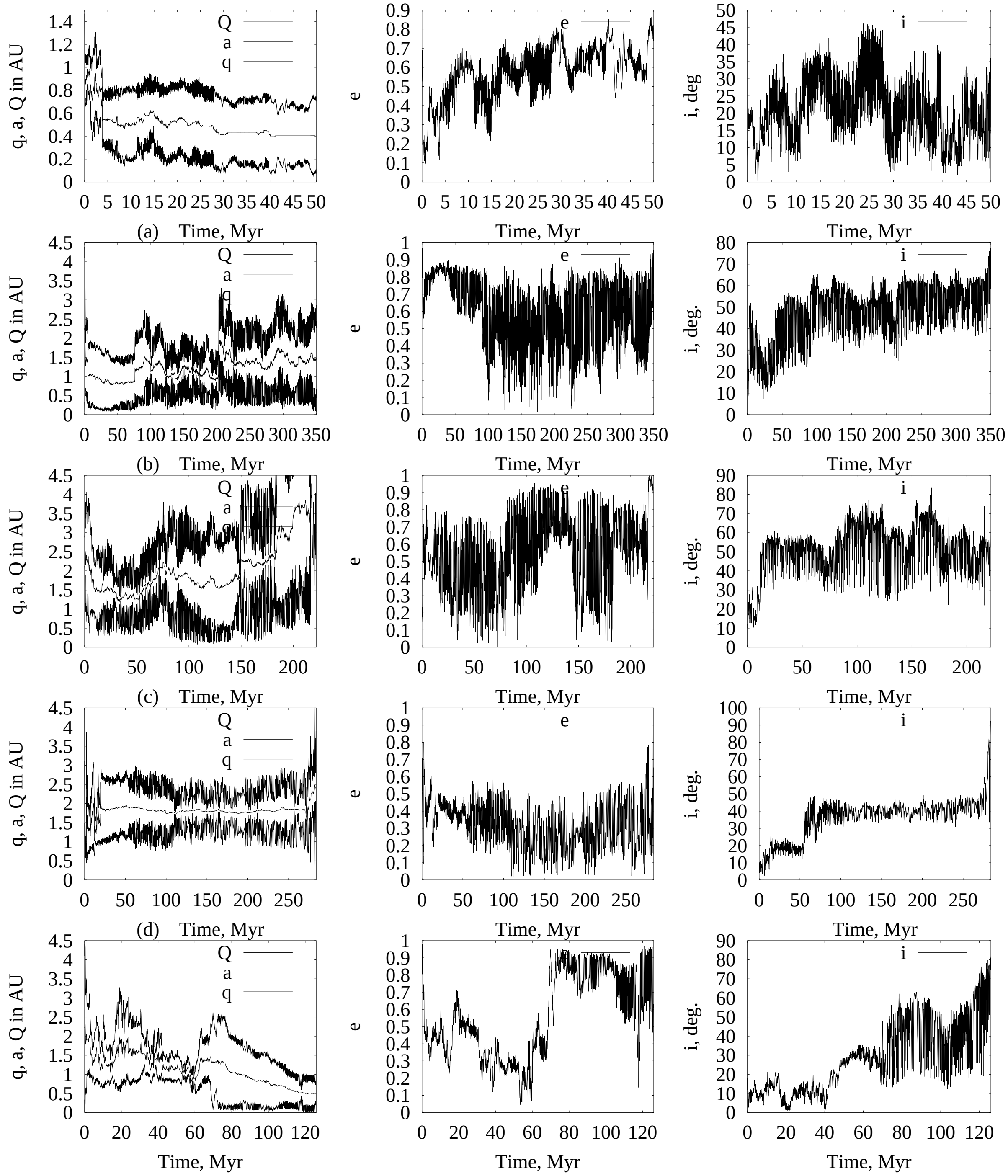


Fig. 2. Time variations in $a$, $e$, $q$, $Q$, and $i$ for a former JCO in initial orbit close to that of Comet 10P (a), 2P (b, e), 9P (d), or an asteroid at the 3/1 resonance with Jupiter (c). For (a) at $t<0.123$ Myr $Q>a>$1.5 AU. Results from BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$ (a-c) and by a symplectic method with $d_s$=30 days (d) and with $d_s$=10 days (e).

orbits dominate the statistics. Only computations with very large numbers of objects can hope to reach accurate conclusions on collision probabilities with the terrestrial planets.

In Fig. 3 we present the time in Myr during which objects had semi-major axes in an interval with a width of 0.005 AU (Figs. 3a-b) or 0.1 AU (Figs. 3c). At 3.3 AU (the 2:1 resonance with Jupiter) there is a gap for asteroids that migrated from the 5:2 resonance and for former JCOs (except 2P).

For the $n1$ data set, $T_J$=0.12 Myr and, while moving in Jupiter-crossing orbits, objects had orbital periods $P_a$<10, 10<$P_a$<20, 20<$P_a$<50, 50<$P_a$<200 yr for 11%, 21%, 21%, and 17% of $T_J$, respectively. Therefore, there are three times as many JCOs as Jupiter-family comets (for which $P_a$<20 yr). We also found that some JCOs, after residing in orbits with aphelia deep inside Jupiter's orbit, transfer for tens of Myr to the trans-Neptunian region, either in low or high eccentricity orbits. We conclude that some of the main belt asteroids may reach typical TNO orbits, and then become scattered-disk objects having high eccentricities, and vice versa. The fraction of objects from the 5:2 resonance that collided with the Earth was only 1/6 of that for the 3:1 resonance. Only a small fraction of the asteroids from the 5:2 resonance reached $a$<2 AU (Fig. 3b).

The distributions of migrating former JCOs (2P and 10P) and resonant asteroids in $a$ and $e$ (left) and in $a$ and $i$ (right) are presented in Fig. 4-5. For each picture we considered 250 migrating objects (288 for Fig. 5), 100 intervals for $a$, and about the same number of intervals for $e$ and $i$. Different designations correspond to different numbers $n$ of orbital elements (calculated with a step of 500 yr) in one bin (in Fig. 4 '<=' means $\leq$). Similar plots for 39P runs were presented in [17]. All the former JCOs reached low eccentricity orbits very rarely with 2<$a$<3.5 AU and 11<$a$<28 AU. There were many positions of objects when their perihelia were close to a semi-major axis of a giant planet, mainly of Jupiter (Fig. 4a). Note that Ozernoy et al. [22] considered the migration of Neptune-crossers and found that the main concentrations of perihelia were near Neptune's orbit.

W. Bottke pointed out that H. Levison showed that it is difficult to detect solar collisions in any numerical integrator, so he removed objects with $q$<$q_{\min}$. The results presented above were obtained considering collisions with the Sun, but we also investigated what happens if we consider $q_{\min}$ equal to $k_S$ radii $r_S$ of the Sun. For $k_S$=2, some results are presented in Fig. 4d-e, 5b. The only difference with the runs that considered collisions with the Sun is that for those runs for series 2P and 10P and for the 3:1 resonance, some objects reached 90°<$i$<180° (mainly with 2<$a$<3.5 AU) (Fig. 4b-c, 5a). For $k_S$=2 there were no comets with $i$>90° and there were only a few orbits of asteroids with $i$>90° (Fig. 4d-e, 5b). The consideration of $q_{\min}$ at $k_S$=3 did not influence the collision probabilities with the terrestrial planets or getting orbits with $a$<2 AU. For example, with BULSTO for the two objects with the largest collision probabilities, the time spent in orbits with $a$<2 AU decreased by only 0.3% for 2P at $k_S$=3 and was the same for 10P at $k_S$=10.

## COMPARISON OF ORBIT INTEGRATORS

To determine the effect of the choice of orbit integrators and convergence criteria, we made additional runs with BULSTO at $\varepsilon$=$10^{-13}$ and $\varepsilon$=$10^{-12}$ and with a symplectic integrator. The orbital evolution of 9551 JCOs was computed with the RMVS3 code. For the symplectic method we usually used an integration step $d_s$ of 3, 10, and 30 days. For series $n2$ and 44P we took different values of $d_s$ between 5 and 10 days.

We find that, exclusive for the case of close encounters with the Sun, the differences between integrator choices (with $d_s\leq$10 days) are comparable to the differences between runs with slightly different initial conditions. Our interpretation is that 1) very small numbers of particles

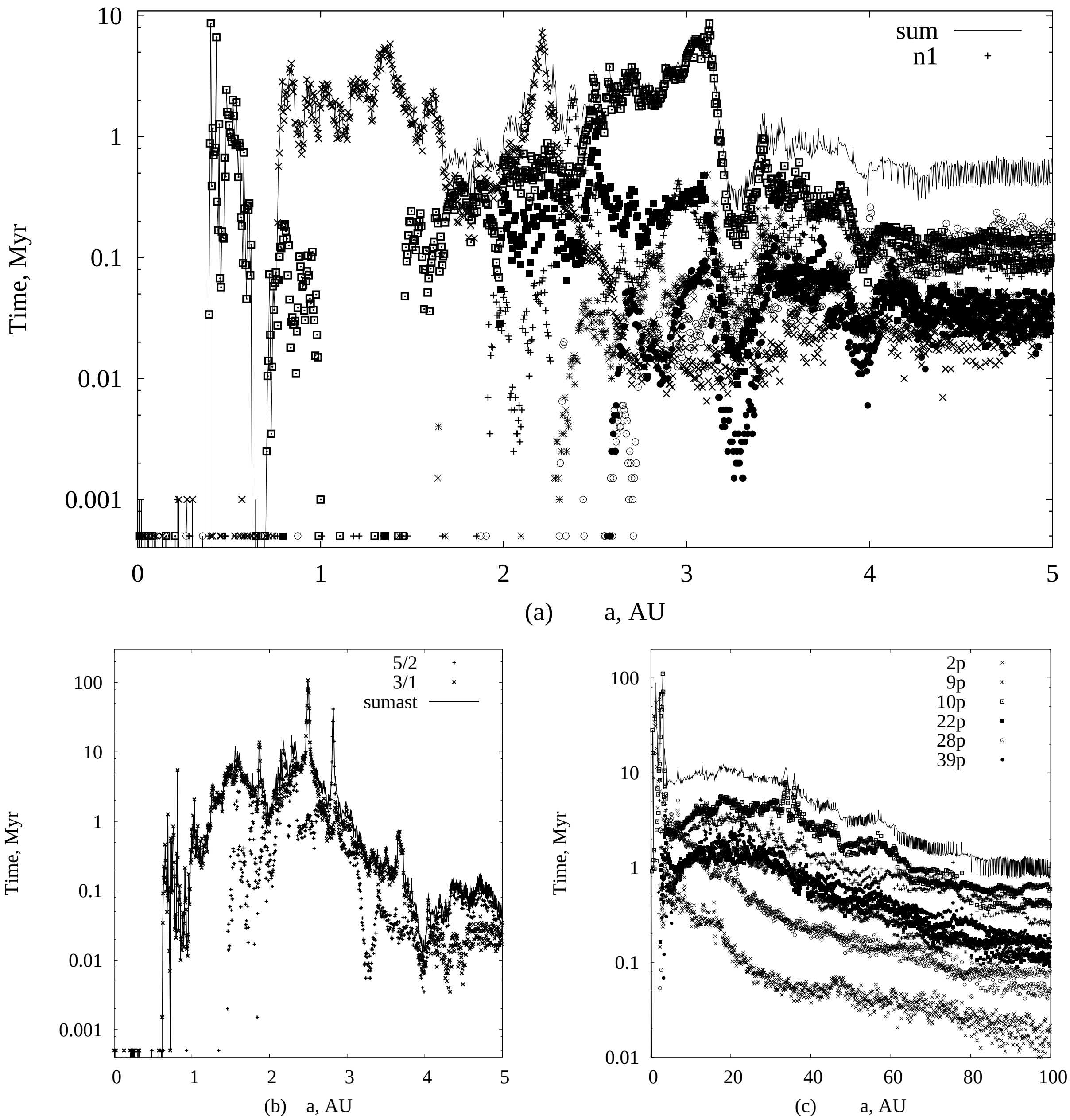


Fig. 3. Distribution of 7852 migrating JCOs (a, c) and 288 resonant asteroids at $e_o$=0.15 and $i_o$=10$^o$ (b) with their semi-major axes. The curves plotted in (c) at $a$=40 AU are (top-to-bottom) for sum, 10P, n1, 39P, 22P, 9P, 28P, and 2P (series n2 and 44P are not included in the figure). For Figs. (a) and (c), designations are the same. Results from BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$.

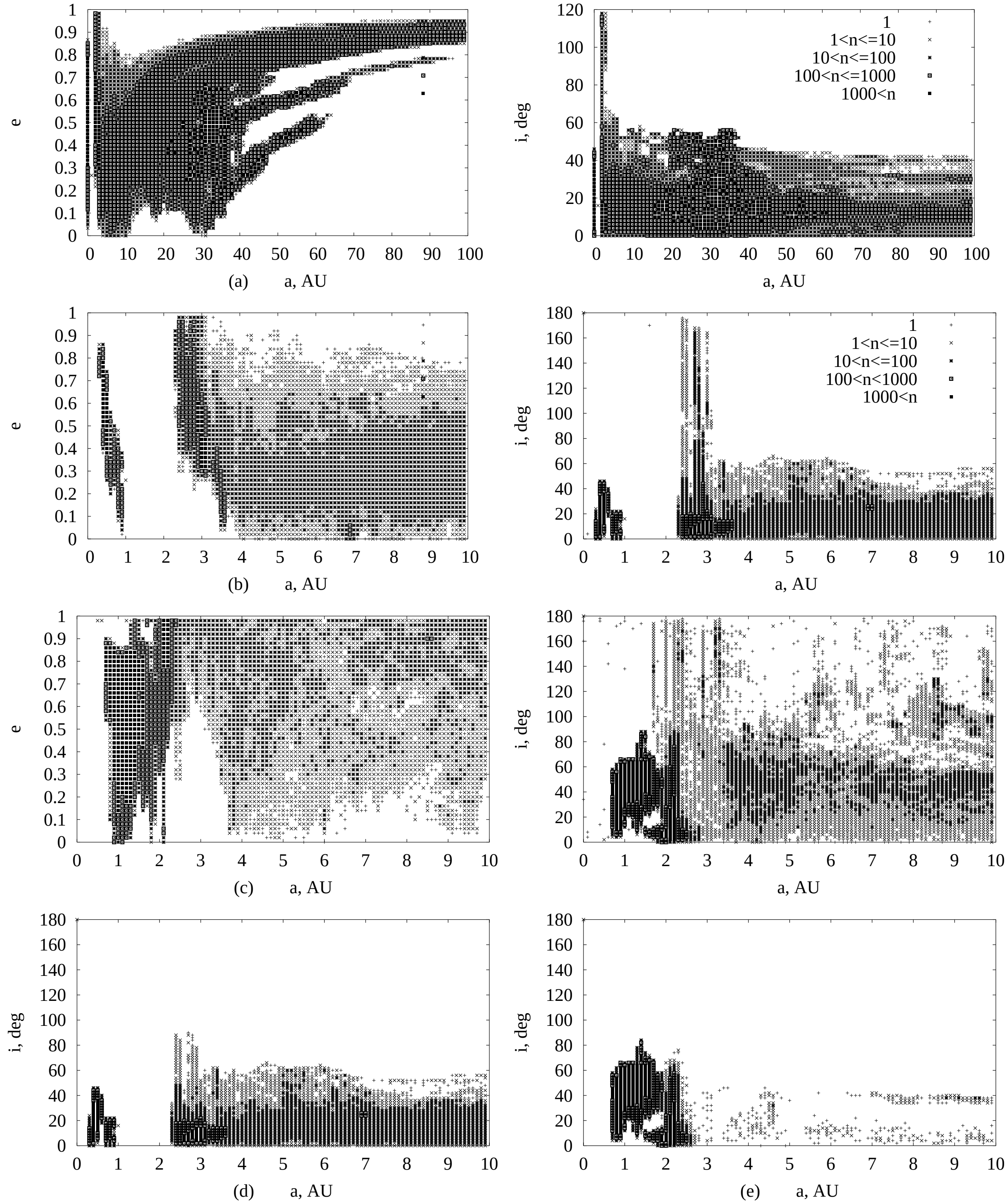


Fig. 4. Distribution of migrating objects in semi-major axes, eccentricities, and inclinations for objects in initial orbits close to that of 10P (a-b,d), 2P (c,e), and BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$. For (d-e) it was considered that an object disappeared when perihelion distance became less than 2 radii of the Sun. In other cases (a-c) objects disappered when they collided with the Sun.

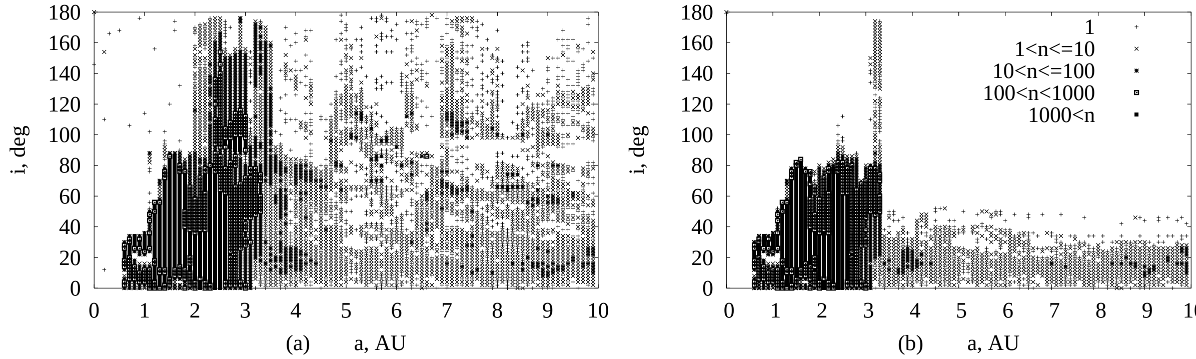


Fig. 5. Distribution of migrating objects in semi-major axes and inclinations for objects in initial orbits at the 3:1 resonance with Jupiter with $e_o$=0.15 and $i_o$=10°. BULSTO code with $\varepsilon \sim 10^{-9} - 10^{-8}$. For (a) objects disappered when they collided with the Sun. For (b) it was considered that an object disappeared when perihelion distance became less than 2 radii of the Sun.

contribute most of the collision probabilities with the terrestrial planets, 2) runs with larger numbers of particles are more reliable, and 3) small differences in initial conditions or in the errors of the orbit integrators modify the trajectories substantially, especially for those particles making major changes in their orbits due to close encounters or resonances. We conclude that for the purposes of this paper, the various choices of orbit integrator are sufficiently equivalent.

To illustrate these points, Tables 3-4 present the results obtained by BULSTO with $\varepsilon \leq 10^{-12}$ and the symplectic method with $d_s \leq 10$ days. Most of the results obtained with these values of $\varepsilon$ and $d_s$ are statistically similar to those obtained for $10^{-9} \leq \varepsilon \leq 10^{-8}$. For example, a few objects spent millions of years in Earth-crossing orbits inside Jupiter's orbit (Figs. 1-2), and their probabilities of collisions with the Earth were thousands of times greater than for more typical objects. For series $n1$ with $d_s \leq 10^d$, the probability of a collision with Earth for one object with initial orbit close to that of Comet 44P was 88.3% of the total probability for 1200 objects from this series, and the total probability for 1198 objects was only 4%. This object and the object presented in Fig. 2e and in the third line of Table 5 were not included in Table 3 with $N$=1199 for $n1$ and with $N$=250 for 2P, respectively. For the 3:1 resonance with $d_s$=10 days, 142 objects spent 140 and 84.5 Myr in IEO and Aten orbits, respectively, even longer than for $\varepsilon \sim 10^{-9}$-$10^{-8}$. Additionally, up to 40 Myr and 20 Myr were spent in such orbits by two other objects which had estimated probabilities of collisions with the terrestrial planets greater than 1. For the 2P runs with $\varepsilon \leq 10^{-12}$ and $N$=100, the calculated objects spent 5.4 Myr in Apollo orbits with $a$<2 AU.

The values of $P_r$ are usually of the same order of magnitude for different methods (see Tables 3-4), and the difference between the data is comparable to the differences between different runs belonging to a series. For Earth and Venus, the values of $P_r$ are about 1–4 for Comets 9P, 22P, 28P and 39P; for Comet 44P they are about 4–6. For 28P and 39P with the symplectic method $P_r$ is about twice that for BULSTO. For 10P the values of $P_r$ are about 20–40 and are several times larger than for the above series, and for 2P they exceed 100 and are several times larger than for 10P. With the $n1$ and $n2$ runs, for Earth $P_r$>4 and $P_r$>10, respectively. The ratio of $P_r$ to the mass of the planet was typically several times larger for Mars than for Earth and Venus. The main difference in $P_r$ was found for the 3:1 resonance. In this case greater

values of $P_r$ were obtained for $d_s$=10 days than for BULSTO. As noted above, a few exceptional objects dominated the probabilities, and for the 3:1 resonance two objects, which had collision probabilities greater than unity for the terrestrial planets, were not included in Table 4. These two objects can increase the total value of $P_r$ for Earth by a factor of several.

The mean time $T_d$ (in Kyr) spent in orbits with $Q$<4.2 AU can differ by three orders of magnitude for different series of runs (Tables 3-4). For most runs (except for 2P and asteroids) the number of objects which got $Q$<4.7 AU was several times larger than that for $Q$<4.2 AU.

For symplectic runs with $d_s$=30 days for most of the objects we got results similar to those with $d_s \leq 10$ days, but about 0.1% of the objects reached Earth-crossing orbits with $a$<2 AU for several tens of Myr (e.g., Fig. 2d) and even IEO orbits. These few bodies increased the mean value of $P$ by a factor of more than 10. With $d_s$=30 days, four objects from the runs $n1$, 9P, 10P had a probability of collisions with the terrestrial planets greater than 1 for each, and for 2P there were 21 such objects among 251 considered. For resonant asteroids, we also obtained much larger values than those for BULSTO for $P$ and $T$ for RMVS3 with $d_s$=30 days, and similarly for the 3:1 resonance even with $d_s$=10 days. For this resonance it may be better to use $d_s$<10 days. Probably, the results of symplectic runs with $d_s$=30 days can be considered as such migration that includes some nongravitational forces.

In the case of close encounters with the Sun (Comet 2P and resonant asteroids), the probability $P_S$ of collisions with the Sun during lifetimes of objects was larger for RMVS3 than for BULSTO, and for $10^{-13} \leq \varepsilon \leq 10^{-12}$ it was greater than for $10^{-9} \leq \varepsilon \leq 10^{-8}$ ($P_S$=0.75 for the 3:1 resonance with $d_s$=3 days). This probability is presented in Table 7 for several runs.

Table 7. Probability of collisions with the Sun (for asteroids $e_o$=0.15 and $i_o$=10$^o$).

| | $\varepsilon = 10^{-13}$ | $\varepsilon = 10^{-12}$ | $\varepsilon = 10^{-9}$ | $\varepsilon = 10^{-8}$ | $d_s$ = 10 days | $d_s$ = 30 days |
|---|---|---|---|---|---|---|
| Comet 2P | 0.88 | 0.88 | 0.38 | 0.32 | 0.99 | 0.8 |
| resonance 3 : 1 | 0.46 | 0.5 | 0.156 | 0.112 | 0.741 | 0.50 |
| resonance 5 : 2 | | 0.06 | 0.062 | 0.028 | 0.099 | 0.155 |

For Comet 2P the values of $T_J$ were much smaller for RMVS3 than those for BULSTO and they were smaller for smaller $\varepsilon$; for other runs these values do not depend much on the method. In our opinion, the most reliable values of $T_J$ were obtained with $10^{-13} \leq \varepsilon \leq 10^{-12}$. In the direct integrations reported by Valsecchi et al. [23], 13 of the 21 objects fell into the Sun, so their value of $P_S$=0.62 is in accordance with our results obtained by BULSTO; it is less than that for $\varepsilon$=$10^{-12}$, but greater than for $\varepsilon$=$10^{-9}$. Note that even for different $P_S$ the data presented in Tables 2-3 usually are similar. As we did not calculate collision probabilities of objects with planets by direct integrations, but instead calculated them with the random phase approximation from the orbital elements, we need not make integrations with extremely high accuracy. We showed [24] that for BULSTO the integrals of motion were conserved better and the plots of orbital elements for closely separated values of $\varepsilon$ were closer to one another with $10^{-9} \leq \varepsilon \leq 10^{-8}$. The smaller the value of $\varepsilon$, the more integrations steps are required, so $\varepsilon \leq 10^{-12}$ for large time intervals are not necessarily better than those for $10^{-9} \leq \varepsilon \leq 10^{-8}$. Small $\varepsilon$ is clearly necessary for close encounters. Therefore we made most of our BULSTO runs with $10^{-9} \leq \varepsilon \leq 10^{-8}$. We found [1],[9] that former JCOs reached resonances more often for BULSTO than for RMVS3 with $d_s$=30 days. For a symplectic method it is better to use smaller $d_s$ at a smaller distance

$R$ from the Sun, but in some runs $R$ can vary considerably during the evolution. The choice of $d_s$ depends on the smallest values of $R$, so a symplectic method with a constant $d_s$ may not be effective when $R$ is very different for different objects considered.

## MIGRATION FROM BEYOND JUPITER TO THE EARTH

The fraction $P_{TNJ}$ of TNOs reaching Jupiter's orbit under the influence of the giant planets in 1 Gyr is 0.8-1.7% [6]. As the mutual gravitational influence of TNOs can play a larger role in variations of their orbital elements than collisions [2], we considered the upper value of $P_{TNJ}$. Using the total of $5 \times 10^9$ 1-km TNOs with $30<a<50$ AU, and assuming that the mean time for a body to move in a Jupiter-crossing orbit is 0.12 Myr, we find that about $N_{Jo}$=$10^4$ 1-km former TNOs are now Jupiter-crossers, and 3000 are Jupiter-family comets. With the total times spent by $N_J$ simulated JCOs in Apollo orbits we can estimate the number of 1-km former TNOs now moving in such orbits using the following formula: $N_{Apollo} = N_{Jo} \cdot t_{Apollo}/(N_J \cdot t_J)$, where $t_{Apollo}$ is the total time during which $N_J$ former JCOs moved in Apollo orbits, and $N_J \cdot t_J$ is the total time during which $N_J$ JCOs moved in Jupiter-crossing orbits. Similar formulas can be considered for other types of orbits. Based on $n1$ and $n2$ series of runs, we obtain that there are about 700-900 Amors and 2000-3000 Apollos (the last numbers include very eccentric orbits) which came from the Edgeworth-Kuiper belt and have diameters greater than 1 km. Even if the number of Apollo objects is an order of magnitude smaller than the above value, it may still be comparable to the real number (750) of 1-km Earth-crossing objects (half of them are in orbits with $a$<2 AU), although the latter number does not include those in highly eccentric orbits.

The ratio $k_2$ of the number of Apollos with $a$<2 AU to the number of all Apollos was very different for different series of runs. It was 0.4 for $n1$ runs, but the total time spent by 3100 considered objects in orbits with $a$<2 AU was due mainly only to one object. For $n2$ series with RMVS3, $k_2$=0.2, but practically all time spent by 6250 objects in orbits with $a$<2 AU was also due to one object. For all JCOs considered, $k_2$ was about 0.5, but the total time spent in orbits with $a$<2 AU was due mainly to the objects from 2P series of runs.

The values of the characteristic time (usually $T_c$) for the collision of a former JCO or a resonant asteroid with a planet (see Tables 3-4) are greater than the values of $T_f$ for NEOs in Table 1, so we expect that the mean inclinations and eccentricities of unobserved NEOs are greater than those for the NEOs that are already known. Similar results were found in [25]. On average, the values of $T_c$ for our $n1$ and $n2$ series and for most of our simulated JCOs were not greater than those for our calculated asteroids, and migrating Earth-crossing objects had similar $e$ and $i$ for both former JCOs and resonant asteroids. Former JCOs, which move in Earth-crossing orbits for more than 1 Myr, while moving in such orbits, usually had larger $P$ and smaller $e$ and $i$ (sometimes similar to those of the observed NEOs, see Figs. 1-2). It is easier to observe orbits with smaller values of $e$ and $i$, and probably, many of the NEOs moving in orbits with large values of $e$ and $i$ have not yet been discovered. About 1% of the observed Apollos cross Jupiter's orbit, and an additional 1% of Apollos have aphelia between 4.7-4.8 AU, but these Jupiter-crossers are far from the Earth most of time, so their actual fraction of ECOs is greater than for observed ECOs. The fraction of Earth-crossers among observed Jupiter-family comets is about 10%. This is a little more than $T/T_J$ for our $n1$ runs, but less than for $n2$ runs. For our former resonant asteroids, $T_J$ is relatively large (≈0.2 Myr), and such asteroids can reach cometary orbits.

Comets are estimated to be active for $T_{act}$∼$10^3$–$10^4$ yr. $T_{act}$ is smaller for closer encounters with the Sun [5], so for Comet 2P it is smaller than for other JFCs. Some former comets can move for tens or even hundreds of Myr in NEO orbits, so the number of extinct comets can exceed the number of active comets by several orders of magnitude. The mean time spent by

Encke-type objects in Earth-crossing orbits is $\geq$0.4 Myr (even for $q_{\min}$). This time corresponds to $\geq$40-400 extinct comets of this type. Note that the diameter of Comet 2P is about 5-10 km, so the number of smaller extinct comets can be much larger.

The above estimates of the number of NEOs are approximate. For example, it is possible that the number of 1-km TNOs is several times smaller than $5 \times 10^9$, while some scientists estimated that this number can be up to $10^{11}$ [13]. Also, the fraction of TNOs that have migrated towards the Earth might be smaller. On the other hand, the above number of TNOs was estimated for $a < 50$ AU, and TNOs from more distant regions can also migrate inward. Probably, the Oort cloud could also supply Jupiter-family comets. According to Asher et al. [26], the rate of a cometary object decoupling from the Jupiter vicinity and transferring to an NEO-like orbit is increased by a factor of 4 or 5 due to nongravitational effects (see also [27]). This would result in larger values of $P_r$ and $T$ than those shown in Table 3.

Our estimates show that, in principle, the trans-Neptunian belt can provide a significant portion of the Earth-crossing objects, although many NEOs clearly came from the main asteroid belt. Many former Jupiter-family comets can have orbits typical of asteroids, and collide with the Earth from typical NEO orbits. It may be possible to explore former TNOs near the Earth's orbit without sending spacecraft to the trans-Neptunian region.

Based on the estimated collision probability $P = 4 \times 10^{-6}$ we find that 1-km former TNOs now collide with the Earth once in 3 Myr. This value of $P$ is smaller than that for our $n1$, and especially than for $n2$, 10P and 2P runs. Assuming the total mass of planetesimals that ever crossed Jupiter's orbit is $\sim 100 m_\oplus$, where $m_\oplus$ is the mass of the Earth [1],[28], we conclude that the total mass of bodies that impacted the Earth is $4 \times 10^{-4} m_\oplus$. If ices comprised only half of this mass, then the total mass of ices $M_{ice}$ that were delivered to the Earth from the feeding zone of the giant planets is about the mass of the terrestrial oceans ($\sim 2 \times 10^{-4} m_\oplus$).

The calculated probabilities of collisions of objects with planets show that the fraction of the mass of the planet delivered by short-period comets can be greater for Mars and Venus than for the Earth (Table 3). This larger mass fraction would result in relatively large ancient oceans on Mars and Venus. On the other hand, there is the deuterium/hydrogen paradox of Earth's oceans, as the D/H ratio is different for oceans and comets. Pavlov et al. [29] suggested that solar wind-implanted hydrogen on interplanetary dust particles could provide the necessary low-D/H component of Earth's water inventory, and Delsemme [30] considered that most of the seawater was brought by the comets that originated in Jupiter's zone, where steam from the inner solar system condensed onto icy interstellar grains before they accreted into larger bodies.

Our estimate of the migration of water to the early Earth is in accordance with [31], but is greater than those of Morbidelli et al. [32] and Levison et al. [33]. The latter obtained smaller values of $M_{ice}$, and we suspect that this is because they did not take into account the migration of bodies into orbits with $Q$<4.5 AU. Perhaps this was because they modeled a relatively small number of objects, and Levison et al. [33] did not take into account the influence of the terrestrial planets. In our runs the probability of a collision of a single object with a terrestrial planet could be much greater than the total probability of thousands of other objects, so the statistics are dominated by rare occurrences that might not appear in smaller simulations. The mean probabilities of collisions can differ by orders of magnitude for different JCOs. Other scientists considered other initial objects and smaller numbers of Jupiter-crossing objects, and did not find decoupling from Jupiter, which is a rare event. We believe there is no contradiction between our present results and the smaller migration of former JCOs to the near-Earth space that was obtained in earlier work, including our own papers (e.g. [9]), where we used the same integration package.

From measured albedos, Fernandez et al. [34] concluded that the fraction of extinct comets among NEOs and unusual asteroids is significant (at least 9% are candidates). The idea that there may be many extinct comets among NEOs was considered by several scientists. Rickman et al. [35] believed that comets played an important and perhaps even dominant role among all km-size Earth impactors. In their opinion, dark spectral classes that might include the ex-comets are severely underrepresented (see also [10]). Our runs showed that if one observes former comets in NEO orbits, then it is probable that they have already moved in such orbits for millions (or at least hundreds of thousands) years, and only a few of them have been in such orbits for short times (a few thousand years). Some former comets that have moved in typical NEO orbits for millions or even hundreds of millions of years, and might have had multiple close encounters with the Sun (some of these encounters can be very close to the Sun, e.g. in the case of Comet 2P at $t$>0.05 Myr), could have lost their mantles, which causes their low albedo, and so change their albedo (for most observed NEOs, the albedo is greater than that for comets [34]) and would look like typical asteroids or some of them could disintegrate into mini-comets. Typical comets have larger rotation periods than typical NEOs [36]-[37], but, while losing considerable portions of their masses, extinct comets can decrease these periods. For better estimates of the portion of extinct comets among NEOs we will need orbit integrations for many more TNOs and JCOs, and wider analysis of observations and craters.

## CONCLUSIONS

Some Jupiter-family comets can reach typical NEO orbits and remain there for millions of years. While the probability of such events is small (about ∼0.1%), nevertheless the majority of collisions of former JCOs with the terrestrial planets are due to such objects. Most former TNOs that have typical NEO orbits moved in such orbits for millions of years (if they did not disintegrate into mini-comets), so during most of this time there were extinct comets. From the dynamical point of view there could be many extinct comets among the NEOs. The amount of water delivered to the Earth during planet formation could be about the mass of the Earth oceans.

## ACKNOWLEDGMENTS

This work was supported by NRC (0158730), NASA (NAG5-10776), INTAS (00-240), and RFBR (01-02-17540). For preparing some data for figures we used some subroutines written by P. Taylor. We are thankful to W. F. Bottke, S. Chesley, and H. F. Levison for helpful discussions.

## REFERENCES

1. Ipatov, S.I. 2000. Migration of Celestial Bodies in the Solar System. Editorial URSS Publishing Company, Moscow. In Russian.
2. Ipatov, S.I. 2001. Comet hazard to the Earth. Advances in Space Research, Elsevier. **28**: 1107-1116.
3. Bottke, W.F., A. Morbidelli, R. Jedicke, et al. 2002. Debiased orbital and absolute magnitude distribution of the near-Earth objects. Icarus. **156**: 399-433.
4. Binzel, R.P., D.F. Lupishko, M. Di Martino, et al. 2002. Physical properties of near-Earth objects. *In* Asteroids III. W. F. Bottke Jr., et al., Eds.: 255-271. University of Arizona, Tucson.
5. Weissman, P.R., W.F. Bottke Jr., H.F. Levison. 2002. Evolution of comets into asteroids. *In* Asteroids III. W. F. Bottke Jr., et al., Eds.: 669-686. University of Arizona, Tucson.
6. Duncan, M.J., H.F. Levison, & S.M. Budd. 1995. The dynamical structure of the Kuiper belt. Astron. J. **110**: 3073-3081.

7. Kuchner, M.J., M.E. Brown, & M. Holman. 2002. Long-term dynamics and the orbital inclinations of the classical Kuiper belt objects. Astron. J. **124**: 1221-1230.

8. Levison, H.F. & M.J. Duncan. 1997. From the Kuiper belt to Jupiter-family comets: The spatial distribution of ecliptic comets. Icarus. **127**: 13-23.

9. Ipatov, S.I. and G.J. Hahn. 1999. Orbital evolution of the P/1996 R2 and P/1996 N2 objects. Solar System Research. **33**: 487-500.

10. Jewitt, D. & Y. Fernandez. 2001. Physical properties of planet-crossing objects. *In* Collisional Processes in the Solar System, M.Ya. Marov & H. Rickman, Eds. ASSL. **261**: 143-161.

11. Ipatov, S.I. 1999. Migration of trans-Neptunian objects to the Earth. Celest. Mech. Dyn. Astron. **73**: 107-116.

12. Jewitt, D., J. Luu, & J. Chen. 1996. The Mauna Kea–Cerro–Tololo (MKCT) Kuiper belt and Centaur survey. Astron. J. **112**: 1225-1238.

13. Jewitt, D. 1999. Kuiper belt objects. Ann. Rev. Earth. Planet. Sci. **27**: 287-312.

14. Ipatov, S.I. 2002. Migration of matter from the Edgeworth–Kuiper and main asteroid belts to the Earth. *In* Dust in the Solar System and Other Planetary Systems, S.F. Green, I.P. Williams, J.A.M. McDonnell & N. McBride, Eds. **15**: 233-236. COSPAR Colloquia Series, Pergamon. http://arXiv.org/format/astro-ph/0205250.

15. Ipatov, S.I. 2002. Formation and migration of trans-Neptunian objects and asteroids. *In* Asteroids, Comets, Meteors: 371-374. http://arXiv.org/format/astro-ph/0211618.

16. Ipatov, S.I. 2003. Formation and migration of trans-Neptunian objects. *In* Scientific Frontiers in Research of Extrasolar Planets, D. Deming & S. Seager, Eds. ASP Conference Series. In press. http://arXiv.org/format/astro-ph/0210131.

17. Ipatov, S.I. and J.C. Mather. 2003. Migration of Jupiter-family comets and resonant asteroids to near-Earth space. *In* Proc. of the international conference "New trends in astrodynamics and applications" (20-22 January 2003, University of Maryland, College Park). CD-ROM (http://arXiv.org/format/astro-ph/0303219).

18. Ipatov, S.I. 1988. Evolution times for disks of planetesimals. Soviet Astronomy. **32 (65)**: 560-566.

19. Bulirsh, R. & J. Stoer. 1966. Numerical treatment of ordinary differential Equations by Extrapolation Methods. Numer. Math. **8**: 1-13.

20. Levison, H.F. & M.J. Duncan. 1994. The long-term dynamical behavior of short-period comets. Icarus. **108**: 18-36.

21. Ipatov, S.I. 1995. Migration of small bodies to the Earth. Solar System Research. **29**: 261-286.

22. Ozernoy, L.M., N.N. Gorkavyi, & T. Taidakova. 2000. Four cometary belts associated with the orbits of giant planets: a new view of the outer solar system's structure emerges from numerical simulations. Planetary and Space Science. **48**: 993-1003.

23. Valsecchi, G.B., A. Morbidelli, R. Gonczi, et al. 1995. The dynamics of objects in orbits resembling that of P/Encke. Icarus. **118**: 169-180.

24. Ipatov, S.I. 1988. The gap problem and asteroid-type resonant orbit evolution. Kinematics and Physics of Celestial Bodies. **4**. N 4: 49-57.

25. Jedicke, R., A. Morbidelli, T. Spahr, et al. 2003. Earth and space-based NEO survey simulations: prospects for achieving the Spaceguard Goal. Icarus. **161**: 17-33.

26. Asher, D.J., M.E. Bailey, & D.I. Steel. 2001. The role of non-gravitational forces in decoupling orbits from Jupiter. *In* Collisional Processes in the Solar System. M.Ya. Marov & H. Rickman, Eds. ASSL. **261**: 121-130.

27. Fernandez, J.A. & T. Gallardo. 2002. Are there many inactive Jupiter-family comets among the near-Earth asteroid population? Icarus. **159**: 358-368.
28. Ipatov, S.I. 1993. Migration of bodies in the accretion of planets, Solar System Research, **27**: 65-79.
29. Pavlov, A.A., A.K. Pavlov, & J.F. Kasting. 1999. Irradiated interplanetary dust particles as a possible solution for the deuterium/hydrogen paradox of Earth's oceans. Journal of Geophysical research. **104**. N. E12: 30,725-30,728.
30. Delsemme, A.H. 1999. The deuterium enrichment observed in recent comets is consistent with the cometary origin of seawater. Planetary and Space Science. **47**: 125-131.
31. Chyba, C. F. 1989. Impact delivery and erosion of planetary oceans in the early inner solar system. Nature. **343**: 129-132.
32. Morbidelli, A., J. Chambers, J.I. Lunine, et al. 2000. Source regions and timescales for the delivery of water to the Earth. Meteoritics & Planetary Science. **35**: 1309-1320.
33. Levison, H.F., Dones, L., Chapman, C.R., et al. 2001. Could the lunar "late heavy bombardment" have been triggered by the formation of Uranus and Neptune?. Icarus. **151**: 286-306.
34. Fernandez, Y.R., Jewitt, D.C., & S.S. Sheppard. 2001. Low albedos among extinct comet candidates. Astrophys. J. bf 553: L197-L200.
35. Rickman, H., J.A. Fernandez, G.Tancredi, & J. Licandro. 2001. The cometary contribution to planetary impact craters. *In* Collisional Processes in the Solar System, M.Ya. Marov & H. Rickman, Eds. ASSL. **261**: 131-142.
36. Binzel, R.P., S.Xu, S.J. Bus, & E. Bowell. 1992. Origins for the near-Earth asteroids. Science. **257**: 779-782.
37. Lupishko, D.F. & T.A. Lupishko. 2001. On the origins of Earth-approaching asteroids. Solar System Research. **35**: 227-233.